

Grid-Tied Test Plan

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Prepared by:
R. Bonn
J. Ginn
S. Gonzalez
505-844-6710

Sandia National Laboratories
505-844-6710

Evaluation Plan for Grid-Tied Photovoltaic Inverters of Less than 10 kW

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1.0 INTRODUCTION

The test plan described below is intended to be a thorough evaluation that can be used for the characterization of any single-phase or three-phase, grid-tied photovoltaic inverter. Sandia plans to evaluate several grid-tied inverters with power outputs below 10 kilowatts. The purpose of these characterizations is to:

1. develop a standard method for evaluating inverters
2. benchmark inverter capability using a single test methodology,
3. ensure that users have all necessary information required for system design, and
4. identify areas where future development may enhance inverter capabilities and performance.

If a test is not applicable, the test is omitted and N/A is entered in the appropriate block on the test report. Although this test plan relies heavily upon other standards, it is not intended to duplicate other testing, such as that described in UL 1741. The test reports are typically three-page documents that report inverter performance. A sample is shown in Appendix B. The tests are largely automated and use a National Instruments Labview-based data acquisition system.

2.0 Test Plan

Prior to testing, the inverter will be configured and checked for shipping damage. Because the evaluation includes long-term operation, the full inverter evaluation will require two months. The inverter test sequence will include a short period (5 days) of parameter characterization in the laboratory followed by a long-term "field configuration" evaluation. The Sandia test configuration includes up to 30 kW of Solec photovoltaic (PV) modules (field configuration); additional dc requirements will be met with other dc sources (laboratory configuration). All tests will be conducted at room temperature. Temperatures of the power bridges will be monitored.

2.1 Inverter Efficiency Evaluation

The efficiency evaluation (P_{ac}/P_{dc}) will measure the inverter efficiency and verify that the maximum power tracker (MPT) is working properly.

2.1.1 Efficiency Evaluation (laboratory configuration)

The inverter efficiency will be evaluated over the entire range of dc operating voltage with varying output power. This will be accomplished by connecting a power supply to the inverter and recording efficiency throughout the dc operating range. In addition to this basic test, the efficiency will be recorded while the inverter is connected to a PV array for the course of a full day.

2.1.2 MPT Evaluation (field configuration)

The MPT will utilize either a solar array simulator or normally illuminated modules. In either case, I-V curves will be acquired and the maximum power point noted. The MPT will then be connected to the circuit and the voltage will be recorded to determine if the MPT is at the maximum power point. This test will be repeated for five different IV curves (i.e. five different inverter output levels).

2.2 Utility Compatibility

This section addresses hazards to utility personnel and equipment, interference with utility operations, and interference with other utility customers. These tests do not include owner

issues. This section is intended to cover a complete list of utility issues for the utility-tied inverter.

2.2.1. Hazard to utility personnel and equipment (anti-islanding evaluation).

This is an evaluation of disconnect times resulting from the conditions defined in Draft 10 of IEEE P929 and from Sandia-defined evaluations. A dc power supply or a PV array powers the inverter. The grid is either an arbitrary waveform generator or the Sandia grid.

The following will be evaluated.

2.2.1.1. Disconnect time for voltage disturbances using a simulated grid (laboratory configuration). The conditions of concern are reproduced from paragraph 5.1.1 of IEEE P929. Local loads are not specified for this test.

Voltage / % of nominal		Maximum Trip Time
V < 60	(V < 50%)	6 cycles
60 ≤ V < 106	(50% ≤ V < 88%)	120 cycles
106 ≤ V ≤ 127	(88% ≤ V ≤ 106%)	Normal Operation
127 < V ≤ 165	(106% < V < 137%)	120 cycles
165 < V	(137% < V)	2 cycles

The inverter should provide no energy to the utility after experiencing the following four conditions. Inverter restart time will be monitored and recorded; the restart time allowed by IEEE 929 is not sooner than 5 minutes.

Test 1. A deviation in voltage from 120 V rms to 59 V rms. The inverter should disconnect in 6 cycles or less.

Test 2. A deviation in voltage from 120 V rms to 105 V rms. The inverter should disconnect in 120 cycles or less.

Test 3. A deviation in voltage from 120 V rms to 128 V rms. The inverter should disconnect in 120 cycles or less.

Test 4. A deviation in voltage from 120 V rms to 166 V rms. The inverter should disconnect in 2 cycles or less.

2.2.1.2 Disconnect time for frequency disturbances using a simulated grid (laboratory configuration). The conditions of concern are from paragraph 5.1.2 of IEEE P929. Annex G further defines the frequency slew rate to be no faster than .5 Hz/s. Local loads are not specified for this test. The inverter should provide no energy to the utility within 6 cycles after experiencing the following two conditions:

Test 5. A deviation in frequency from 60 Hz to 60.6 Hz with a slew rate < .5 Hz/s. Disconnect time is measured from the time the frequency is > 60.5 Hz.

Test 6. A deviation in frequency from 60 Hz to 59.4 Hz with a slew rate < .5 Hz/s. Disconnect time is measured from the time the frequency is < 59.5 Hz.

2.2.1.3 Disconnect time for special load conditions using actual grid (laboratory configuration). These loads are listed below.

Test 7. A resonant LRC load with a Q of 2.5 and P_{gen}/P_{load} ratio of 1. The inverter should disconnect in less than 2 seconds.

Test 8. A resistive load with a $P_{\text{gen}}/P_{\text{load}}$ ratio of 1.5. The inverter should disconnect in 10 cycles or less.

Test 9. A resistive load with a $P_{\text{gen}}/P_{\text{load}}$ ratio of .5. The inverter should disconnect in 10 cycles or less.

Test 10. An RC load with a power factor of .94 leading. The inverter should disconnect in 10 cycles or less.

Test 11. An RL load with a power factor of .94 lagging. The inverter should disconnect in 10 cycles or less.

2.2.1.4 Disconnect times for multiple inverters on a single-grid feeder (field configuration). There are additional complexities when multiple inverters are running in parallel.

Test 12. Configure two “non-islanding” inverters of different types operating on the same branch circuit with a local load. With a resistive load, match the inverters’ combined output power. Interrupt utility power and monitor each inverter disconnect time. Reconnect the power after 30 seconds and monitor each inverter restart.

2.2.2 Other Potential Utility Issues.

2.2.2.1 Amplitudes of Conducted Noise at Switching Frequencies (laboratory configuration):

Measure conducted switching frequency amplitudes at a distance of ten feet from the inverter. The intent is to quantify signals that have the potential to interfere with carrier wave communication and relay operations. Frequencies of interest are between 3 and 300 kHz. Evaluation conditions include full power and nominal utility line voltage.

2.2.2.2 Power Factor (field configuration):

The power factor will be recorded while the inverter is powered from the PV array for the duration of one sunny day.

2.2.2.3 dc Injection (field configuration):

Both polarities of the inverter output signal will be recorded and integrated so that any dc component can be detected and quantified.

2.2.3. Interference with other utility customers

2.2.3.1 Total Harmonic Distortion (THD) (field configuration).

Measure voltage and current THD and individual harmonic amplitudes up to 3 kHz.¹ Ensure that measurements are made when the inverter is delivering 100% of rated power and that the line harmonics are less than .5% when the inverter is not energized.

¹ IEEE 519. Guide for Harmonic Control & Reactive Compensation of Static Power Converters.

2.2.3.2 Electromagnetic Interference (EMI)^{2&3} (inverter in laboratory using PV).

Measure conducted EMI on both the ac and dc lines. Ensure that these levels are in compliance with FCC regulations and that all significant radiation above 300 kHz is quantified. (Note: dc power supplies may generate rf noise, and therefore this test is performed using solar input power).

Amplitudes of Conducted Radiation: The conducted signal may be measured in either of two manners.⁴ The first uses a LISN (line stabilization network) whose purpose is to provide a uniform impedance between the device under test (DUT) and the line and also provide a monitoring point. Thus this approach should provide consistent measurements when conducted in different locations; however, the conducted emissions in the final situation are likely to differ somewhat from those measured.

The second approach utilizes a line probe. This approach is easier to implement and provides exactly the correct answer when the test is conducted *in situ*. When used in a laboratory environment, the line probe answer will provide a slightly different result than the installed system.

Sandia has a detailed procedure for conducting these measurements.

Amplitudes of radiated rfi (radiated radio frequency interference): Measure radiated noise, preferably at a distance of 3 meters; closer measurements should result in higher magnitude signals. Sandia has never recorded radiated signals in the FCC spectrum of concern (i.e. 30 to 1000 MHz.) that exceed the FCC limits. Because of the need for dc power and ac lines during any active inverter test, the inverters are not tested in a remote location as suggested in reference 5. Furthermore, since radiated energy would be contained, shielded enclosures are not useful for this measurement. The approach used at Sandia for these measurements is to record the radiated rfi and ignore the narrow band spikes from local radio stations. Rfi energy generated from switching devices is wide-band, and thus will fill the space between narrow-band signals. It is easily detected as a rise in the noise floor. Oscillators and clocks in inverters are so far below 30 MHz that they do not contribute to the radiated signals. An SNL test procedure details the test methodology.

2.3. User Issues

The user issues include reliability and usability. A reliable system has minimal unscheduled down-time. This includes failures and nuisance trips. A useable system causes the customer few problems.

2.3.1 dc Operating Range (field configuration).

Quantify the dc operating range. Record the inverter start voltage, stop voltage, and the maximum open circuit voltage that the inverter can respond to.

2.3.2 Acoustic Noise (either configuration).

Record a single noise reading in dB at a distance of .5 meters and using the A filter. Spectral information, which may be valuable for identifying the source of the noise, will be recorded with the C filter in use.

² FCC Part 15, Rules and Regulations, Radio Frequency Devices, July 1981

³ Bulletin OST 52, Jun 1981, Interpretations of the FCC Rules for Computing Devices (Part 15 Subpart J)

⁴ FCC/OET MP-4 (1987), "FCC Procedure for measuring rf Emissions from Computing Devices".

2.3.3 Surge Protection (laboratory configuration)

Provide all inverter inputs with the following pulses^{5&6&7}.,

- 100 kHz ring wave (6 kilovolts open circuit)
- 1.2 by 50 microsecond (6 kilovolts open circuit)
- 8 by 20 microsecond (3 kiloamp short circuit) pulse

Pulse levels will initiate at 1,000 volts (open circuit voltage) and increment up to 6,000 volts in 1,000-volt steps. Measure pulse levels which are coupled through surge protection circuits. Because of the potential for inverter damage, this will be the last test. The transfer functions are provided to the manufacturer. The results will be recorded in the following table.

Pulse	Voltage level where effect is noted	Effect
1.2 by 50 microsecond		
8 by 20 microsecond		
100 kHz ring wave		

2.3.4 Nuisance Trips.

Record any nuisance trips and reconnection times that are longer than the IEEE 929 recommendation (currently 5 minutes).

⁵ ANSI C37.90.1-89, IEEE Standard "Surge Withstand Capability (SwC) Tests for Protective Relays and Relay Systems."

⁶ IEEE C62.41-91, "IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits"

⁷ UL 1741, "Static Inverters and Charge Controllers for use in Photovoltaic Power Systems," 1st Edition, May 7, 1999.

2.3.5 Features

Document the following features that the inverter has.

Feature	Yes	No	Comments
diagnostic receptacle			
on/off switch			
maintenance disconnects			
diagnostics			
indicators			
ground fault detection			
smoke detector			
over temperature shutdown			
mode indicator			
over current protection ⁸			
grounding lugs			
markings ⁹			
remote disable			
remote restart			
PV disconnect ¹⁰			
surge arrestors (ac)			
surge arrestors (dc)			
other			

⁸ National Electrical Code Article 690-9.

⁹ National Electrical Code Article 690-52.

¹⁰ IEEE 1374 "Guide for Terrestrial PV Power System Safety", Sept 98.

Appendix A: Terms and Definitions

1. **Static Power Converter (inverter).** Any static power inverter with control, protection, and filtering functions used to interface an electric energy source with an electric utility system. Sometimes referred to as power conditioning subsystems, power conversions systems, solid-state converters, or power conditioning units.
2. **Islanding.** Operation of the inverter (producing energy) and part of the utility load while isolated from the remainder of the electric utility system.
3. **Voltage Notch.** A switching (or other) disturbance of the normal power voltage wave-form, lasting less than a half-cycle, that reduces the magnitude of the normal signal. This includes complete loss of voltage for up to a half cycle.
4. **Utility Interconnection Point.** Point of interconnection between the utility-owned equipment and that of the inverter owner. This is usually a metering location or service entrance panel.
5. **Total Harmonic Distortion.** The ratio of the rms value of the sum of the squared individual harmonic amplitudes to the rms value of the fundamental frequency of a complex waveform.
6. **Total Distortion.** A measure of the difference between a pure sine waveform of a specified frequency and a test voltage waveform. Usually measured by an audio distortion analyzer.
7. **Sag.** An rms reduction in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds¹¹.
8. **Transient.** A subcycle disturbance in the ac waveform that is evidenced by a sharp brief discontinuity of the waveform. May be of either polarity and may be additive to or subtractive from the nominal waveform¹².
9. **Acoustic Noise.** Quantified by the decibel sound pressure level, dB spl. It is referenced to 20 micropascals of pressure. It is frequently weighted with an overlaid filter. The C filter is a linear filter which is standardized, while the A filter is an audible noise filter with a bandwidth of 500 to 5000 Hz.
10. **PCS Shutdown.** A term that describes a de-energized inverter (PCS) that is not supplying ac energy to the grid.
11. **Island.** The continued operation (supplying energy to the grid) of an inverter after utility power has been disconnected. Failure to shutdown creates a potential hazard for utility maintenance people or may result in an out-of-phase reapplication of the utility power to the PCS. When this happens, an 'Island' of power is left on.
12. **Back-feed.** Per NEC Article 690-9 (FPN), possible back feed of current from any source of supply, including a supply through a power conditioning unit into the photovoltaic output circuit and photovoltaic source circuits, must be considered in determining whether adequate over current protection from all sources is provided for conductors and modules.
13. **DC injection.** Injection of dc into a utility transformer can contribute to transformer saturation. Levels of pure dc equal to 5% of the ac current rating of the transformer, when the transformer is loaded to 70% of its capacity, can produce saturation in approximately 1.1 sec. Higher levels (average dc), were ac resets the transformer core, may not produce saturation.

¹¹IEEE Std 1100-1992, Emerald Book, "Powering and Grounding Sensitive Electronic Equipment"

¹²IEEE Std 1100-1992, Emerald Book, "Powering and Grounding Sensitive Electronic Equipment"

14. Disconnect, Automatic. Per NEC Article 690-61 the power output from a power conditioning unit in a solar photovoltaic system that is interactive with another electric system(s) shall be automatically disconnected from all ungrounded conductors in such other electric system(s) upon loss of voltage in that electric system(s) and shall not reconnect to that electric system(s) until its voltage is restored.
15. PCS Marking. Per Article NEC 690-52A a marking, specifying the photovoltaic power source rated: (1) operating current, (2) operating voltage, (3) open-circuit voltage, and (4) short-circuit current, shall be provided at an accessible location at the disconnecting means for the photovoltaic power source.
16. Power Transformer over current protection. Per the NEC Article 690-9(b), a transformer with a source(s) on each side shall be provided over current protection in accordance with Section 450-3 by considering first one side of the transformer, then the other side of the transformer, as the primary. Exception: A power transformer with a current rating on the side connected toward the photovoltaic power source not less than the short-circuit output current rating of the power conditioning unit shall be permitted without over current protection from that source.

Appendix B: Grid-Tied Inverter Test Report of the Brand X Inverter

Manufacturer's Specifications

Model evaluated	GC1000S	Output Voltage	
Rated power	1000 watts (nom)	current distortion	
Rated volt-amps	not specified	dc startup voltage	
Efficiency	93%	dc maximum voltage	
Fre operating range	59.5 to 60.5 Hz	dc operating range	
		ac operating range	

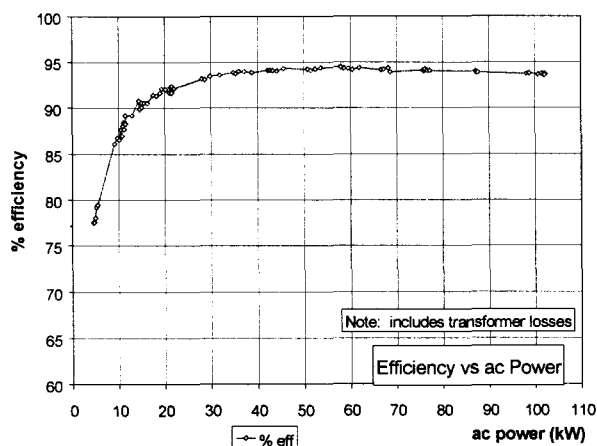
dc Evaluation

Parameter	Quantity
dc ripple voltage peak (bulk)	
dc ripple current peak (bulk)	
connect voltage	
dc operating range	

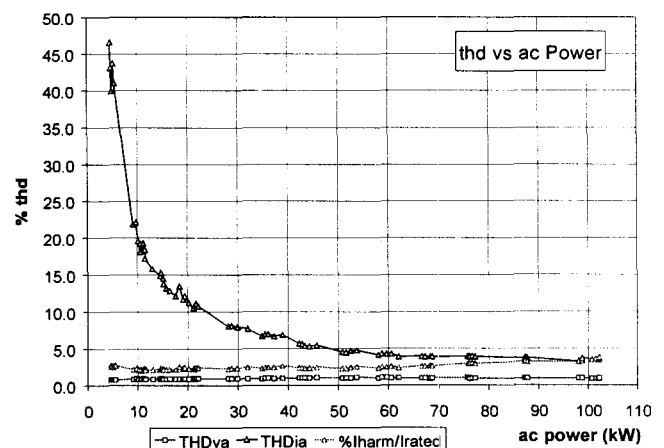
Maximum Power Tracker (MPT) Functionality

Curve tracer P_{max}	Inverter dc power	% error

Efficiency⁽²⁾



Distortion vs ac Power



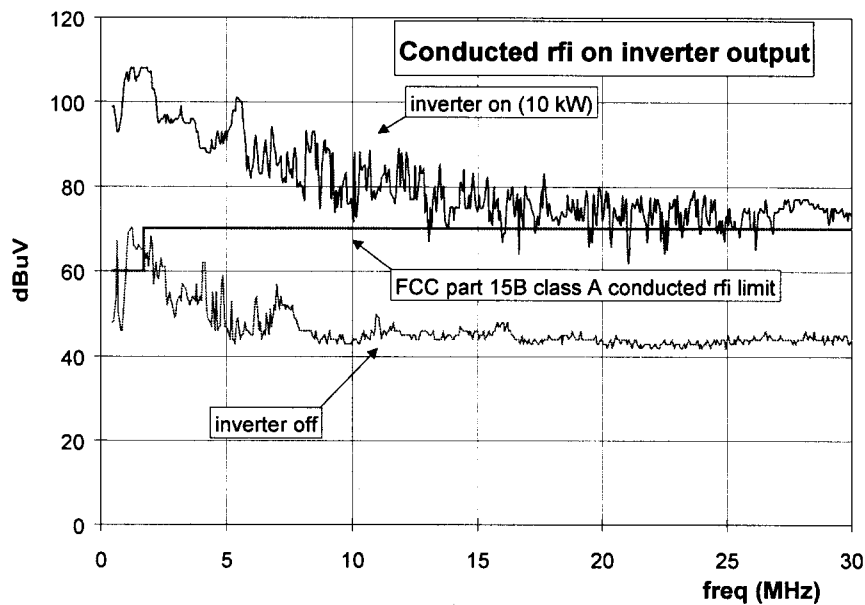
Anti-islanding

voltage deviations	expected max time	measured trip time
$V < 60$ ($V < 50\%$)	6 cycles	
$60 \leq V < 106$ ($50\% < V < 88\%$)	120 cycles	
$106 \leq V \leq 127$ ($88\% \leq V \leq 106\%$)	Normal Operation	
$127 < V \leq 165$ ($106\% < V < 137\%$)	120 cycles	
$165 < V$ ($137\% < V$)	2 cycles	
frequency deviations		
60 Hz to 60.6 Hz, $\Delta f < .5$ Hz/s		
60 Hz to 59.4 Hz, $\Delta f < .5$ Hz/s		
special loads		
R load, matched to inv output power	2 seconds	
LRC load, $Q = 2.5$ and $P_{gen}/P_{load} = 1$	2 seconds	
resistive load, $P_{gen}/P_{load} = 1.5$	10 cycles	
resistive load, $P_{gen}/P_{load} = .5$	10 cycles	
RL load, pf = .95 leading	10 cycles	
multiple inverters		
resistive load, $P_{gen}/P_{load} = 1.0$	10 cycles	

Re-connect Time

reconnect time = _____ minutes

Conducted rfi



Surge Testing

Pulse	Voltage level where effect is noted	Effect
1.2 by 50 microsecond		
8 by 20 microsecond		
100 kHz ring wave		

Feature Evaluation

feature	Yes	No	Comments
diagnostic receptacle			
on/off switch			
maintenance disconnects			
diagnostics			
indicators			
ground fault detection			
smoke detector			
over temperature shutdown			
mode indicator			
over current protection			
grounding lugs			
markings			
remote disable			
remote restart			
PV disconnect			
surge arrestors (ac)			
surge arrestors (dc)			
other			